



# **CMS: The Compact Muon Solenoid Experiment**

Fermilab Annual Users Meeting  
Joel Butler  
June 5, 2008



# Outline

- **A little about the LHC**
- **What is the CMS Detector?**
- **Who is US CMS?**
- **Is the CMS Detector ready to take data?**
- **Is CMS ready to process data?**
- **Is CMS ready to analyze data and do physics?**
- **What might early physics look like?**

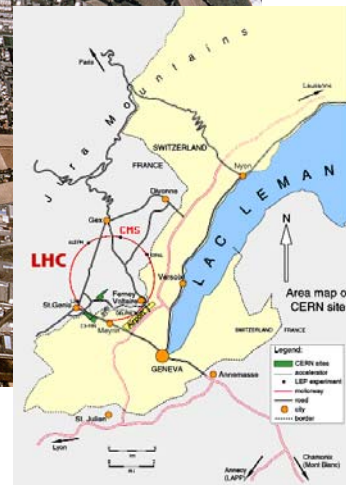
**Looking ahead, the physics landscape is so broad that there is plenty of room for good people to join us to process and analyze the data we will be collecting**

Not covered: CMS Upgrade, which follows the HEP (e.g. D0) tradition of starting to plan an upgrade before the detector ever sees particles collide.



# 1. A little about the LHC at CERN

A machine that collides two beams of 7 TeV protons, producing ~1 billion interactions per second







# LHC - a Few Facts for Experimenters

- **Injection**
  - ◆ From SPS (Super Proton Synchrotron)
  - ◆ 450 GeV/c
- **Energy in each proton beam (peak) 7 TeV**
  - ◆ Stored energy in each beam is 350 MJ (Tevatron ~2MJ)
  - ◆ Current in each beam: 0.5 A
- **Expected luminosity**
  - ◆  $10^{34}/\text{cm}^2\text{-s}$  (achieved after a few years of running)
- **Beams are bunched. Spacing is 25 ns (2808 bunches)**
  - ◆ Protons/bunch at peak luminosity:  $1 \times 10^{11}$ .
  - ◆ Spot size:  $\sim 10\text{-}30 \mu\text{m}$  ( $\beta^* = \sim 50\text{cm}$ )
- **At design luminosity 20 minimum bias events per beam crossing**
  - ◆ One billion collisions/second
  - ◆ Thousands of particles produced per beam crossing – a major detector challenge to sustain the high radiation levels and to sort out  $\langle 20 \rangle$  interactions

**Early running: 5TeV x 5TeV**

**Luminosity:  $10^{30}\text{cm}^{-2}\text{s}^{-1} \rightarrow 10^{32}\text{cm}^{-2}\text{s}^{-1}$**

**# of bunches: 43  $\rightarrow$  156**



## 2. CMS Design Features

- **Very large solenoid – 6m diameter x 13 m long**
  - ◆ Tracking and calorimetry fits inside the solenoid
    - Particle energies are measured before they pass through the solenoid coil and cryostat, which would degrade their resolution
- **Very strong field – 4T**
  - ◆ Coils up soft charged particles
  - ◆ Excellent momentum resolution
- **Tracking chambers in the return iron track and identify muons**
  - ◆ This makes the system very compact
  - ◆ Weight of CMS is dominated by all the steel and is 12,500 Tonnes
- **Tracking is based on all-silicon components**
  - ◆ A silicon pixel detector (66 million pixels) out to ~ 15 cm
  - ◆ A silicon microstrip detector (11 million strips) from 30 cm out to 1.2 m
  - ◆ Gives CMS excellent charged particle tracking and primary and secondary vertex reconstruction
  - ◆ High segmentation results in very low occupancy
  - ◆ Silicon detectors are very radiation hard



# The CMS Detector

**SUPERCONDUCTING  
COIL**

**CALORIMETERS**

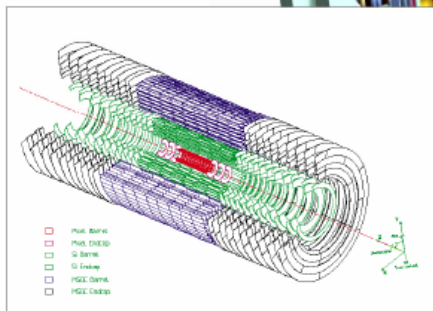
**ECAL** Scintillating  $\text{PbWO}_4$   
Crystals

**HCAL** Plastic scintillator

copper  
sandwich

**IRON YOKE**

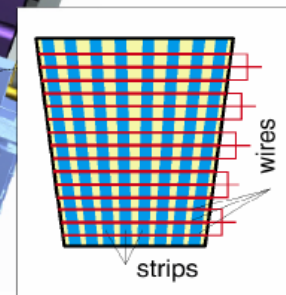
**TRACKERS**



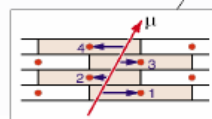
Silicon Microstrips  
Pixels

Total weight : 12,500 t  
Overall diameter : 15 m  
Overall length : 21.6 m  
Magnetic field : 4 Tesla

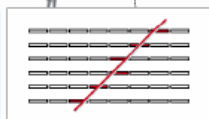
**MUON  
ENDCAPS**



**MUON BARREL**



Drift Tube  
Chambers (DT)



Resistive Plate  
Chambers (RPC)

Cathode Strip Chambers (CSC)  
Resistive Plate Chambers (RPC)

**Total weight: 12,500 Tons**

**Diameter: 15m**

**Length: 21 m**

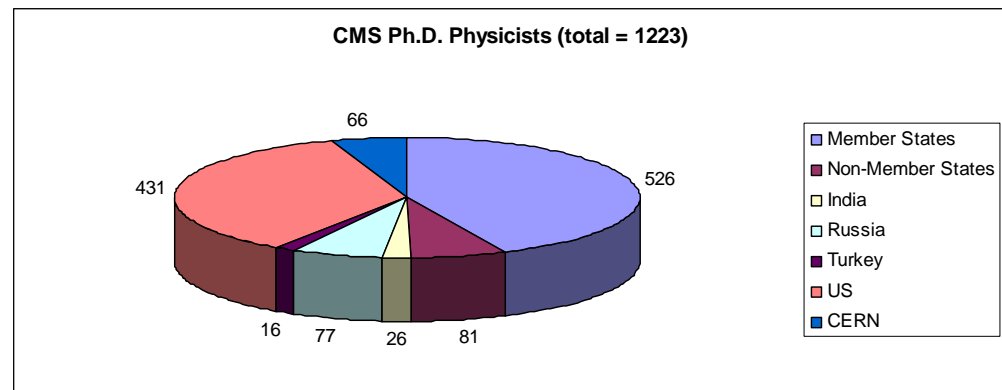
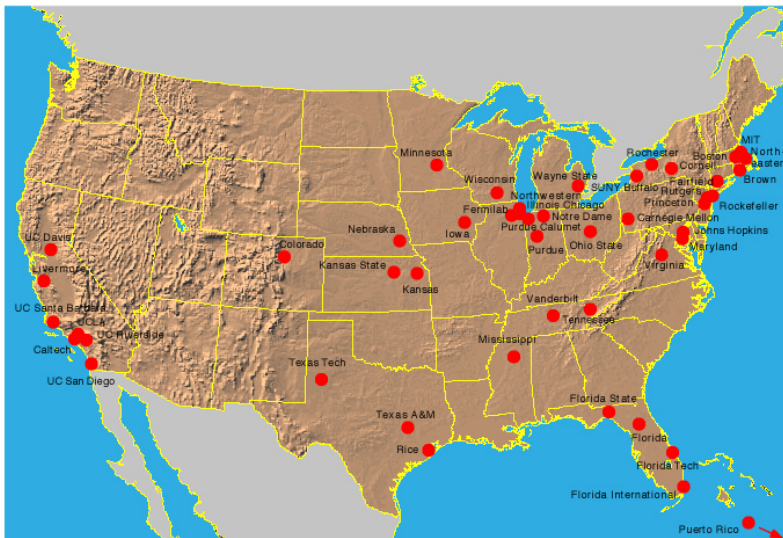
**Field: 4 Tesla**

**Readout channels: ~80M**



### 3. Who is US CMS (Demographics)?

- US CMS consists of 48 institutions out of 160 in 40 countries in all CMS
- It has 826 scientists out of 2848
- It has 431 out of the 1223 Ph.D. physicists in CMS (35%)
  - Of these, 18 are supported by US DOE/NSF NP
- There are currently 203 graduate students in US CMS out of 613 total in CMS

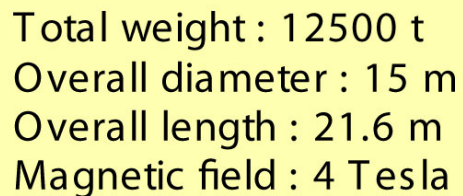




# US Contributions to CMS

- **DOE and NSF contributed \$167M towards construction of CMS**
  - ◆ Magnet
  - ◆ Hadron Calorimeter
  - ◆ Endcap Muon
  - ◆ Forward Pixels
  - ◆ Tracker Outer Barrel Silicon Strips
  - ◆ Electromagnetic Calorimeter Read out and Electronics
  - ◆ Trigger and DAQ
- **Computing Facilities: Tier 1 Computing Center at FNAL and 7 Tier 2 Computing Centers at US Universities**
  - ◆ A great deal of key software for infrastructure, frameworks, and physics
- **Other key facilities**
  - ◆ LHC Physics Center (LPC) at Fermilab
  - ◆ Remote Operations Center at Fermilab



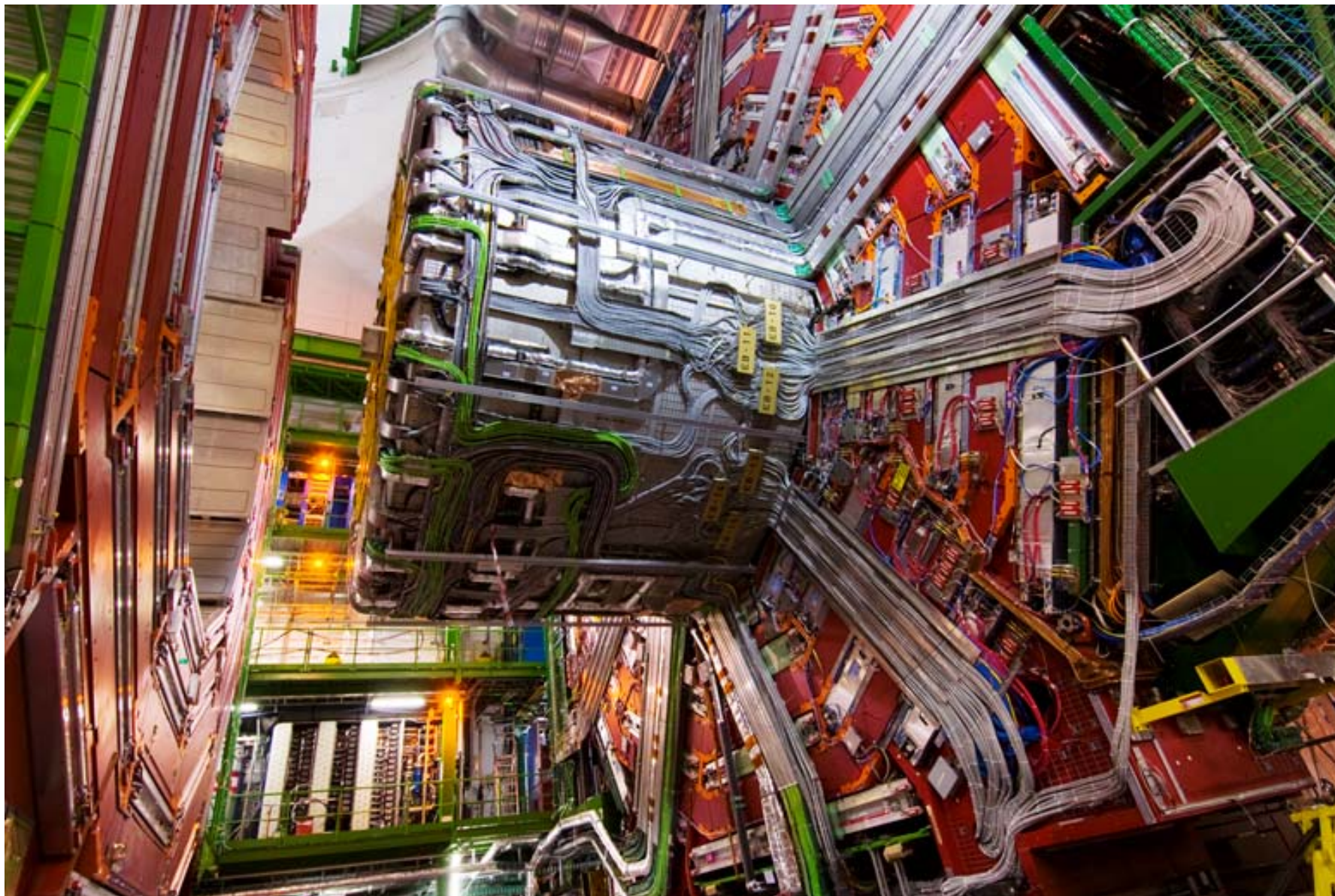


<http://cms.cern.ch>





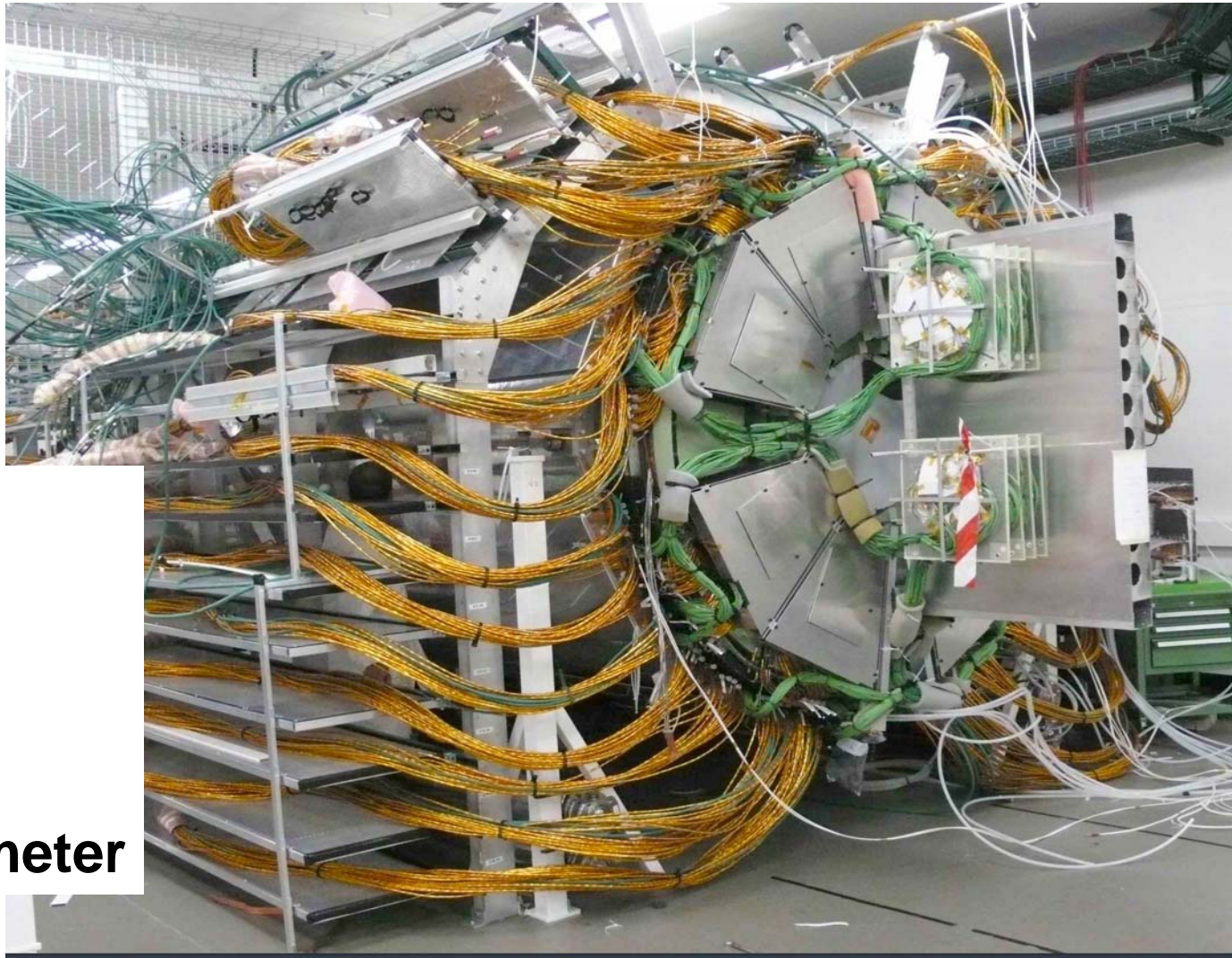
# YB0 Services







# Completed Tracker



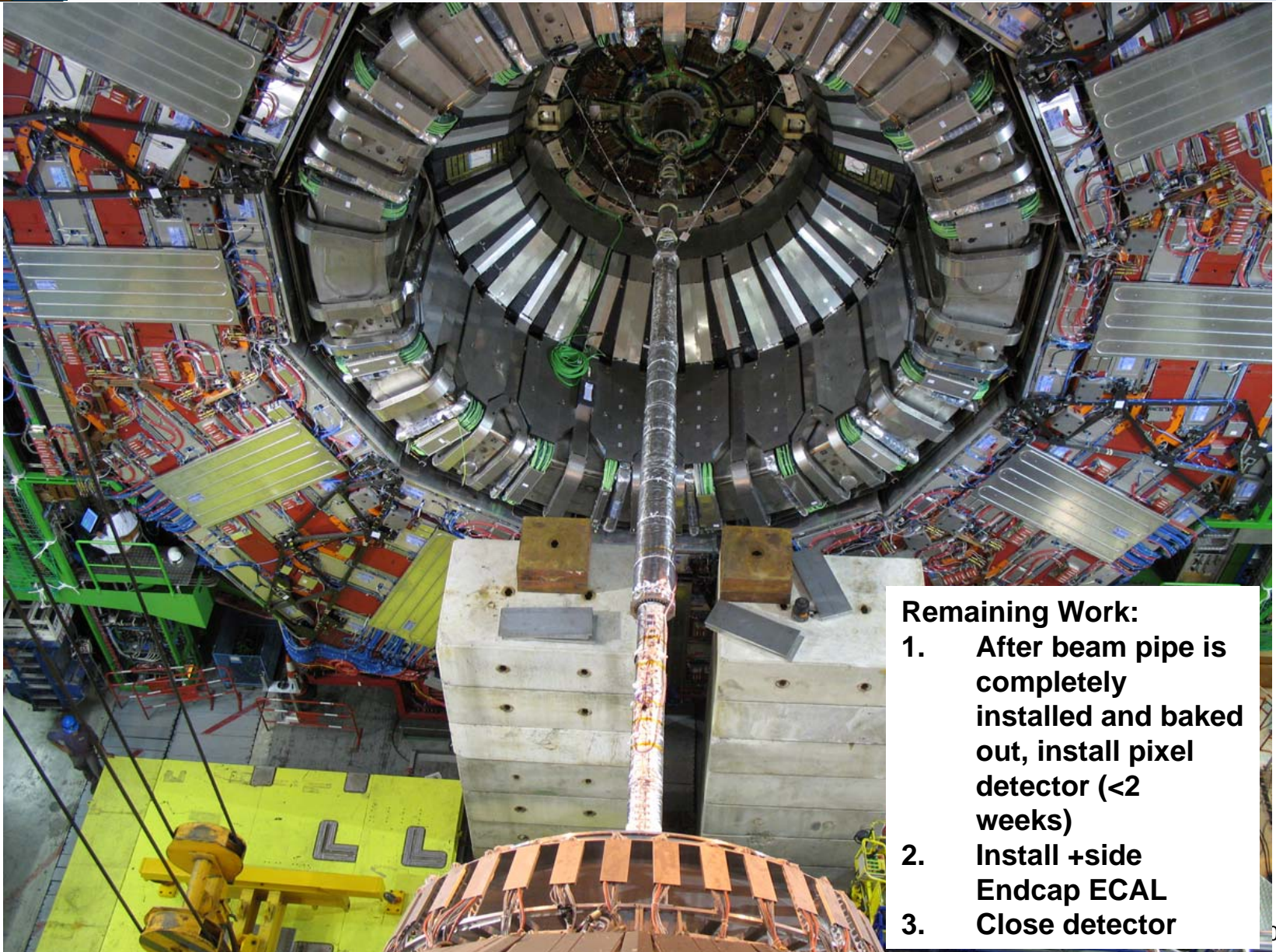
**11 Million  
Channels**

**200 m<sup>2</sup> Si**

**2.4 m diameter**



# Minus-side Beam-pipe Installed



## Remaining Work:

1. After beam pipe is completely installed and baked out, install pixel detector (<2 weeks)
2. Install +side Endcap ECAL
3. Close detector





# BPIX and FPIX

**-x side**



**BPIX at PSI  
awaiting  
installation**



**FPIX at CERN  
awaiting  
installation**

**BPIX & FPIX will be ready for installation by end of May.  
They cannot be installed until the beam pipe is baked out.  
That should be done at the end of June**



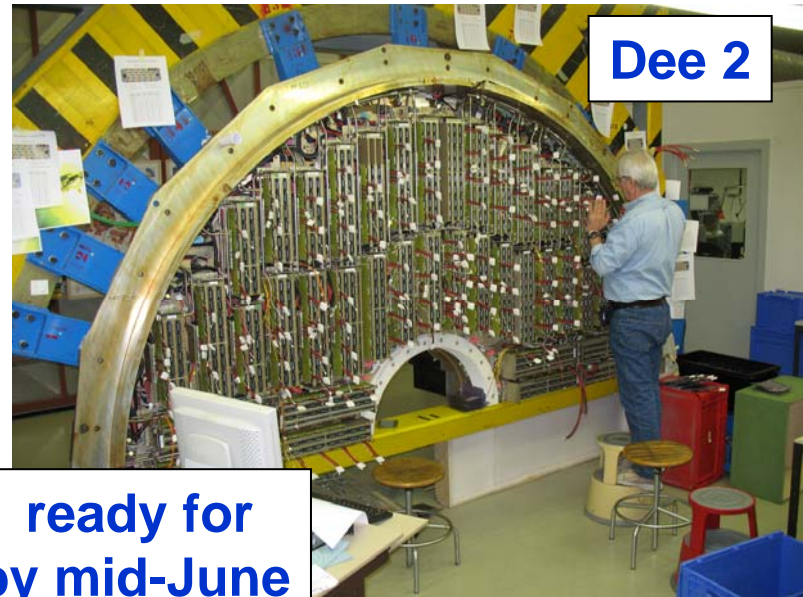


# ECAL Electromagnetic Calorimeter Progress

Dee 1

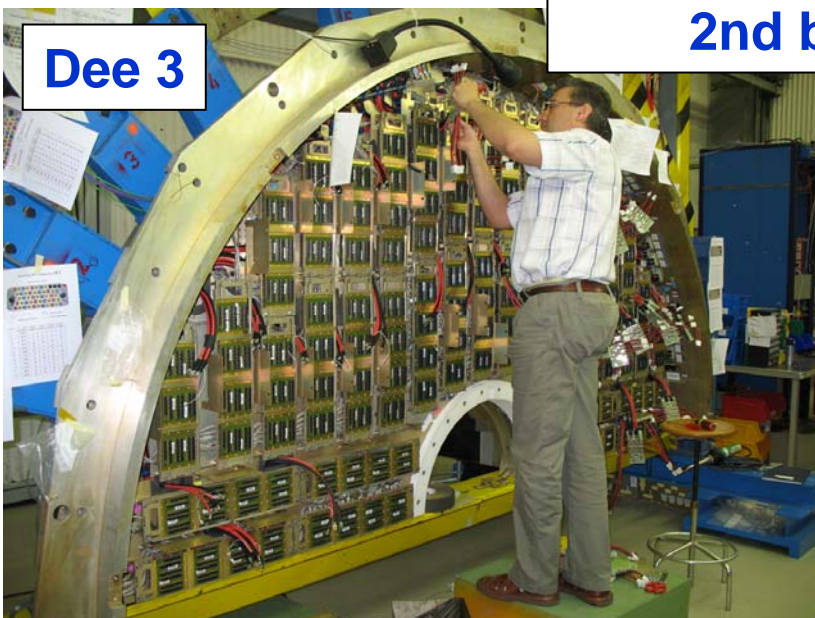


Dee 2

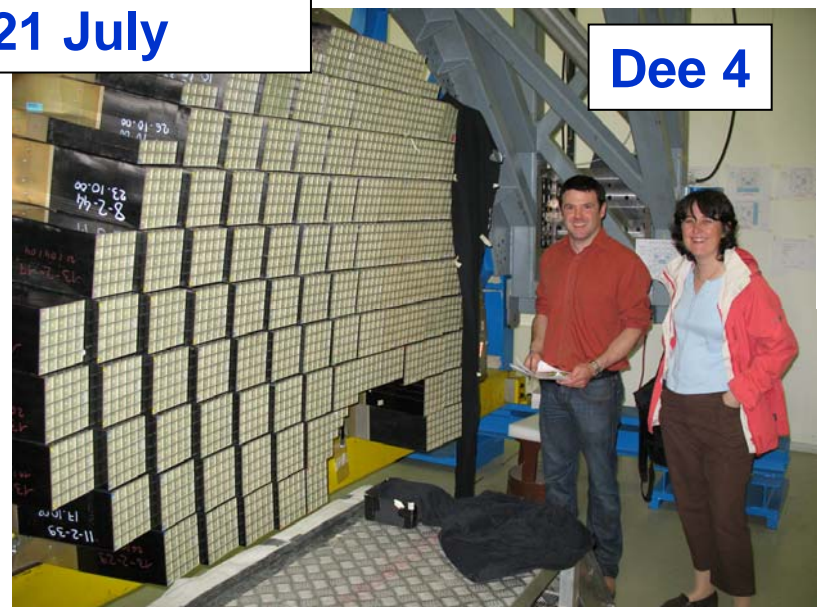


1st end cap ready for  
Installation by mid-June  
2nd by 21 July

Dee 3



Dee 4





# Preparation for the LHC startup

- **In the absence of collisions CMS has prepared for data taking and analysis using**
  - ◆ **Test beam studies**
  - ◆ **Detailed runs using CMS's extensive calibration systems**
  - ◆ **Extensive cosmic ray and noise runs**
  - ◆ **Monte Carlo studies that introduce whatever real performance characteristics are known about the detector**
- **To exercise the computing production, it has taken data from all the above sources and processed it through the full analysis chain**



# Recent and Planned Exercises

- **Cosmic RUN at ZERO Tesla, a.k.a. CRUZET1 (completed in early May)**
  - ◆ **Functionality and performance tests of sub-detectors (excl Tracker)**
- **Combined Computing Readiness Run, CCRC and Computing, Software and Analysis 08, CSA08 (currently running)**
  - ◆ **CCRC: 4 week challenge in May**
    - **A stress test of computing operations for data-taking at scale simultaneously with other expts.**
  - ◆ **CSA08: CMS offline workflows to demonstrate readiness for LHC data (calibration, skims, 4 express analyses)**
    - **Focus on 1, 10 pb-1 scenarios**
- **Cosmic Run at 0T, a.k.a. CRUZET2 (~ beg June, ~ beg July)**
  - ◆ **Functionality and performance tests of sub-detectors (incl Tracker)**
- **Cosmic Run at Four Tesla, a.k.a. CRAFT (~ end July)**
  - ◆ **Test of magnet and the sub-detectors + CMS online and offline workflows to demonstrate readiness for data-taking operations**
- **Followed by Beam!**
  - **Single beam, beam halo, beam-gas,**
  - **Collisions!!**





## 5. Is CMS ready to take and process data?

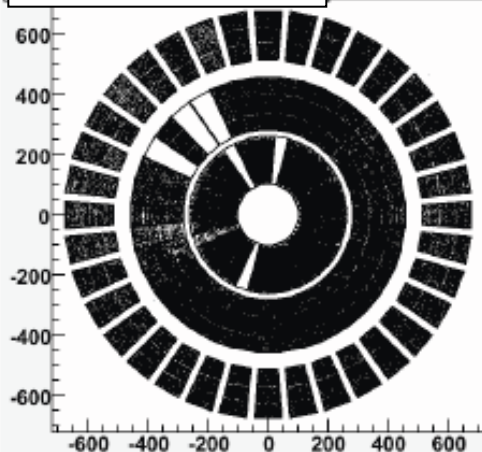
- **From CRUZET1, May 5 – 9, 2008 (24 hour operation beginning May 6)**
- **Operated a substantial fraction of the experiment**
  - ◆ **Muons:** DT (85%), RB (20%), CSCs (50% - one endcap)
  - ◆ **Calorimeters:** ECAL barrel: 100% HCAL: 100%
  - ◆ **Level-1 Trigger:** all muon triggers, ECAL and HCAL coincidence mip triggers
  - ◆ **DAQ and HLT:** 177 builder unit and 533 filter unit processors
  - ◆ **Pixel:** “Panel In Box” for operational experience
- **Sustained runs lasting many hours at 240Hz trigger rate. Logged more than 30M cosmic muon events**
  - **Prompt reconstruction of runs at Tier-0 computing centre with a latency of less than 1 hour**
  - **Data copied to CMS Analysis Facility and to Tier-1, -2 centres**
  - **Data quality monitoring online (served from storage manager) and offline (running at Tier-0).**
- **First results shown on the Friday May 9**

**LOW LATENCY IS A PRIMARY GOAL!**



# CRUZET1: Example Plots: CSCs

station 1



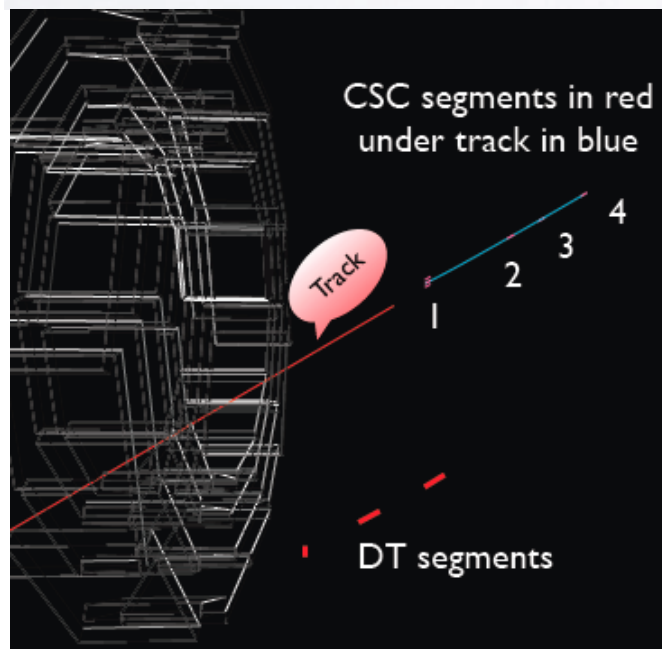
station 2



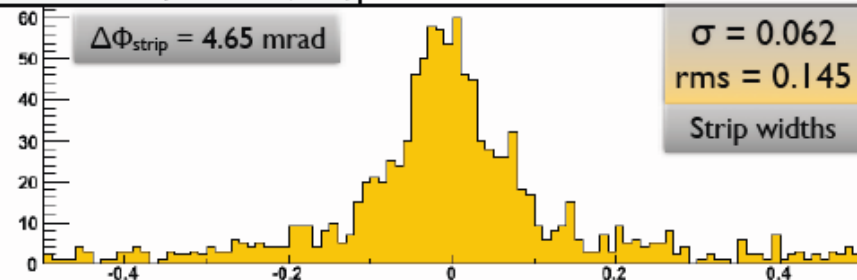
station 3



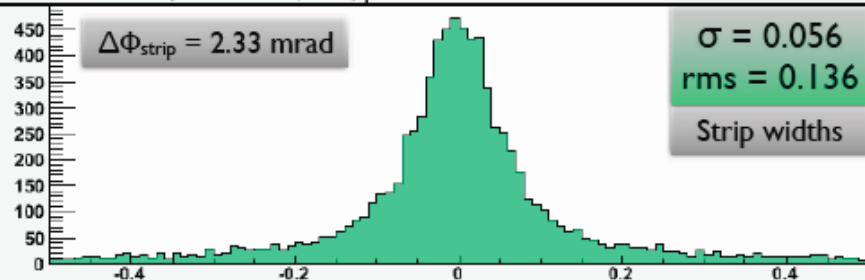
station 4



Fitted Position on Strip - Reco Pos (ME21)



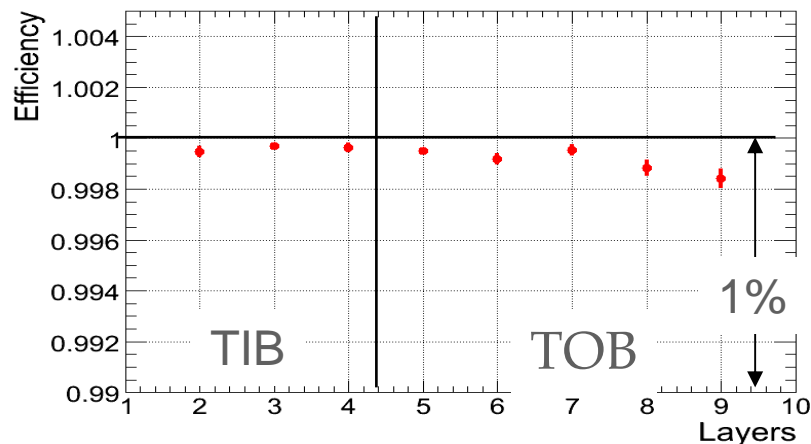
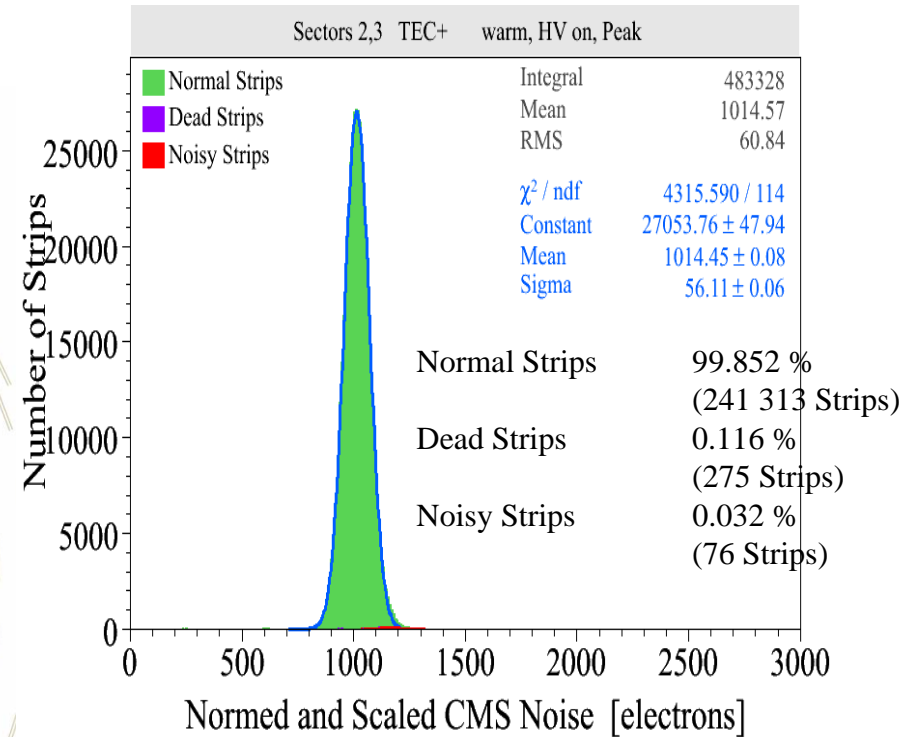
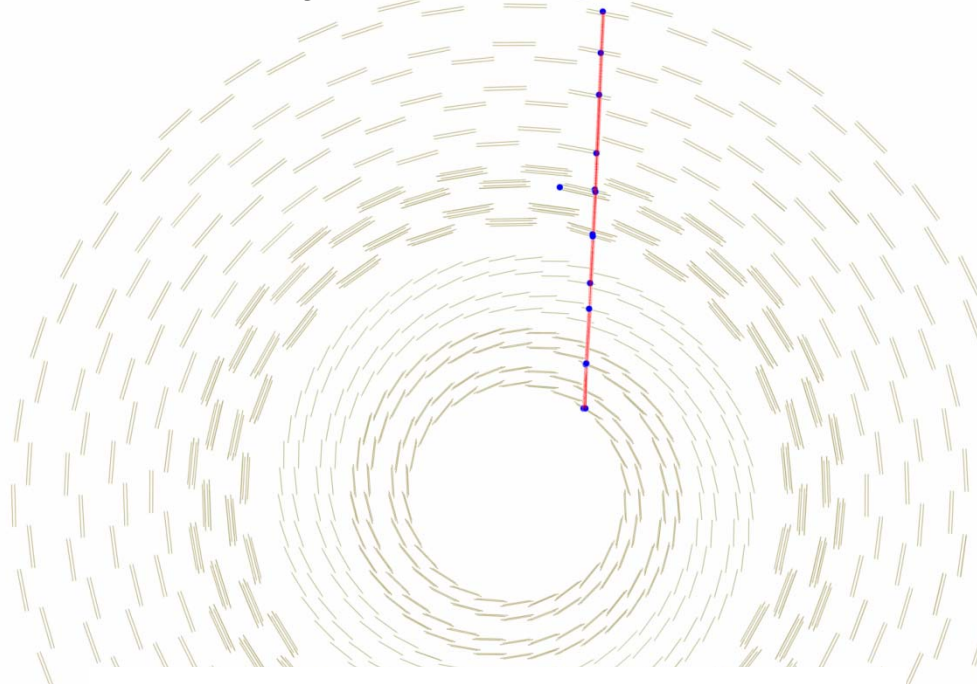
Fitted Position on Strip - Reco Pos (ME32)





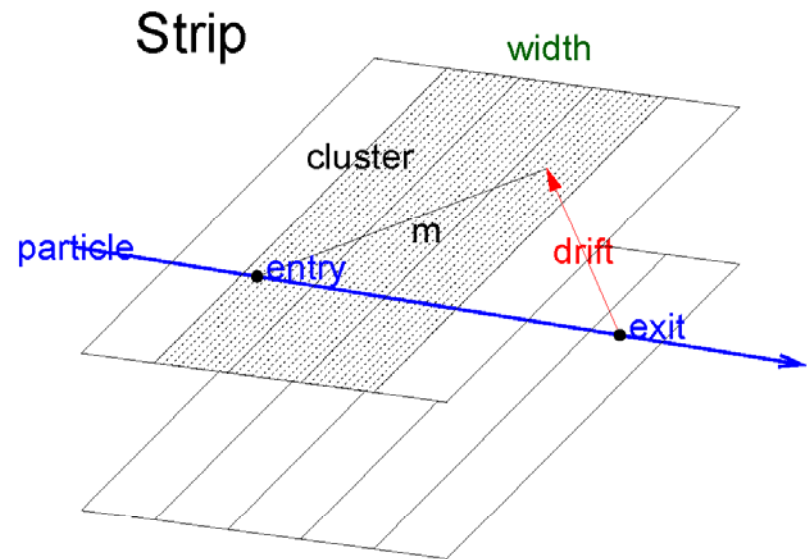
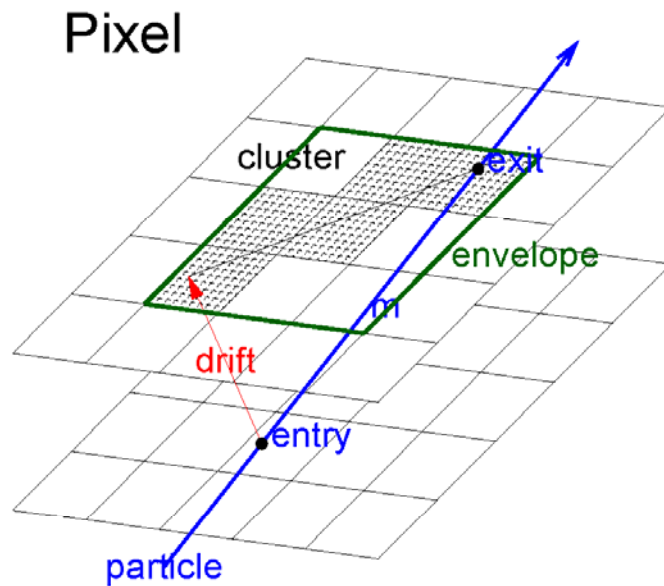
# Cosmics in the Tracker

## Cosmic ray - tracker at -15°C





# Track & Trajectory Filters – Cluster Shape



Cluster shape must match trajectory direction

Developed superb tracking algorithms that make full use of an all silicon system. Attacking such methods early will teach us a lot very quickly.





# CSA08

**Schedule was kept for essential components of CSA08**

Week 1 (5-11 May) S43 prompt reconstruction at T0

Week 2 (12-18 May): **S43 (1pb<sup>-1</sup>) prompt calibration/alignment exercises on CAF**  
S156 prompt reconstruction at T0

Week 3 (19-25 May): **S156 (10pb<sup>-1</sup>) prompt calibration/alignment exercises on CAF**  
S43 re-reco at T1s using constants from S43 exercises

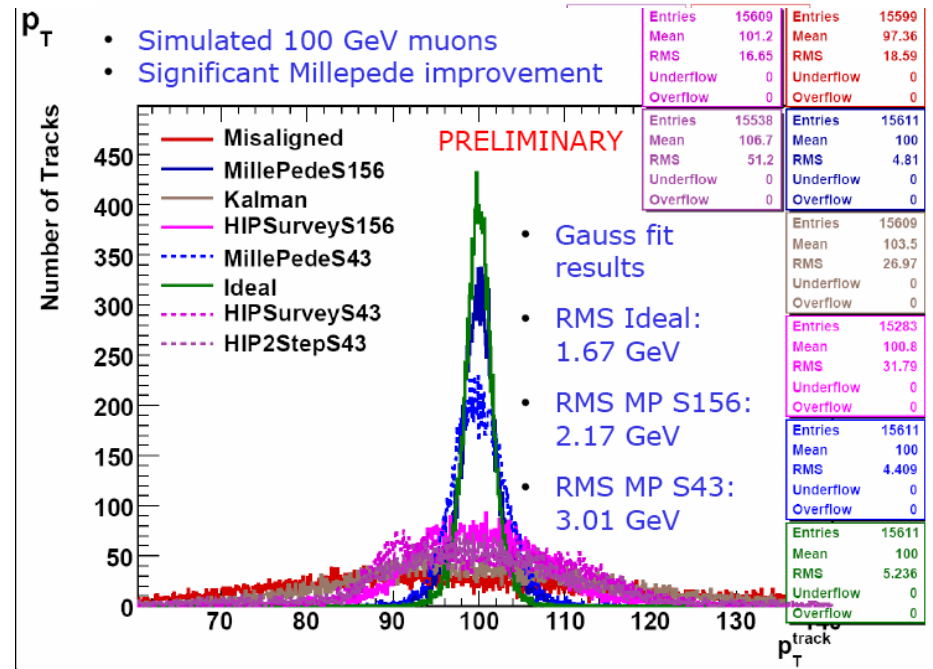
Week 4 (26May- 1Jun): S156 re-reco at T1s using constants from S156 exercises

**All CSA08 production to stop 2nd June**

From June 2: Physics analyses using re-reco S156 data at CAF/T2s (already started in wk 3).

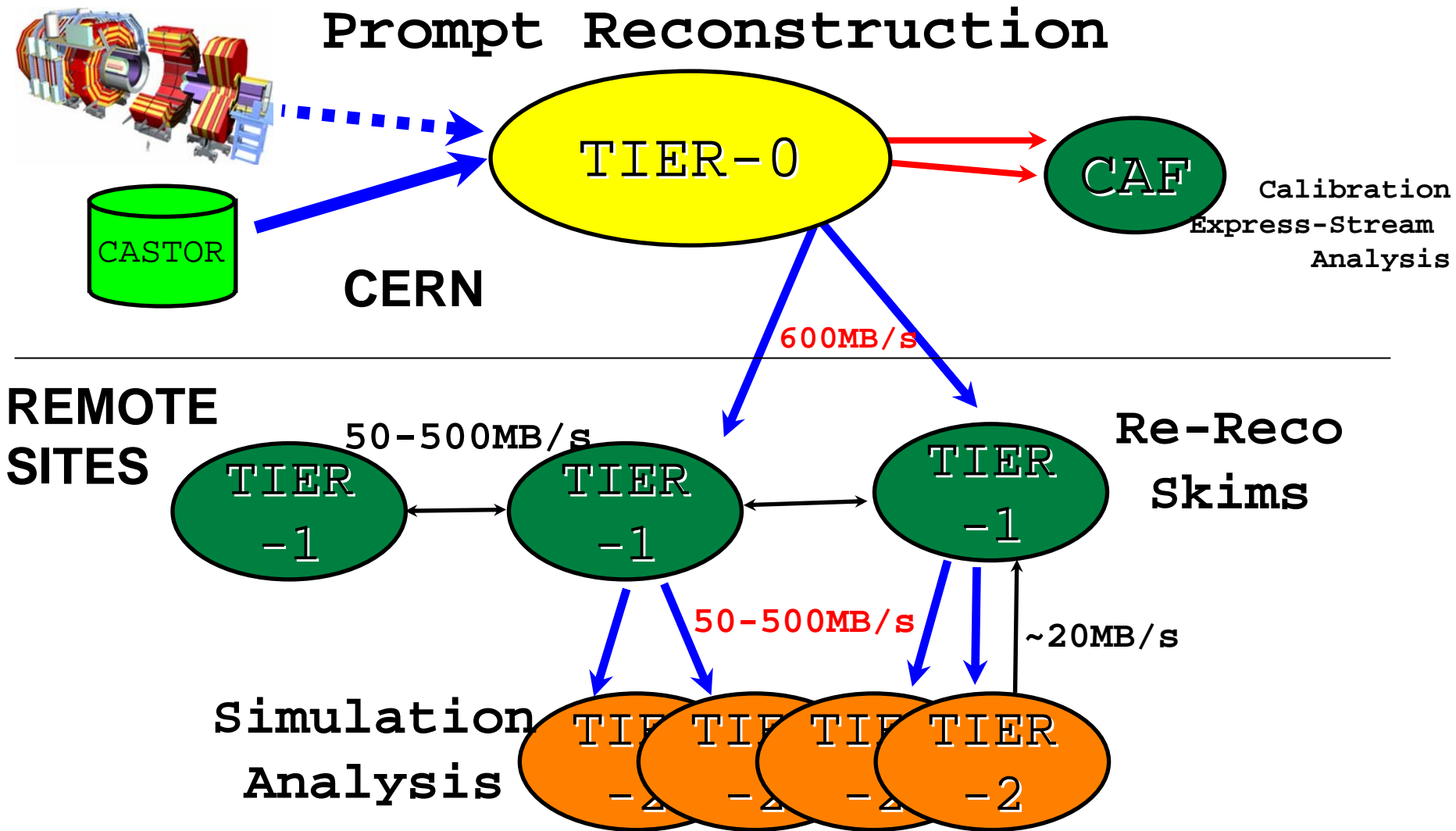
## Example: Preliminary Results from Tracker Alignment (r- $\phi$ ) ( $\mu\text{m}$ )

	0pb <sup>-1</sup>	1pb <sup>-1</sup>	10pb <sup>-1</sup>
Bpix	105	6	3
Fpix	120	48	48
TOB	105	30	23
TIB	480	24	10
TID	445	48	38
TEC	90	29	26





# CCRC/CSA Workflows





# US Tier 1 and Tier 2 Status

- **FNAL is a dedicated Tier-1 Facility for CMS**
- **Meeting the obligations of the U.S. to CMS Production Computing**
- **The only Tier-1 center for CMS in the Americas**
- **Sufficient for 2008 data**
- **FNAL is the largest Tier-1 center in CMS**

US CMS FNAL Tier-1 and LPC Spring 2008	CPU T1	5.5MSI2k	Tier-1 Processing Nodes
	CPU LPC	2.5MSI2k	Dedicated Local Analysis
	Disk T1	2.2PB	dCache (1600MB/s IO)
	Disk LPC	0.5PB	Dedicated to Local Analysis
	Network	20Gb/s	CERN to FNAL
	People	30FTE	Includes Developers and Ops

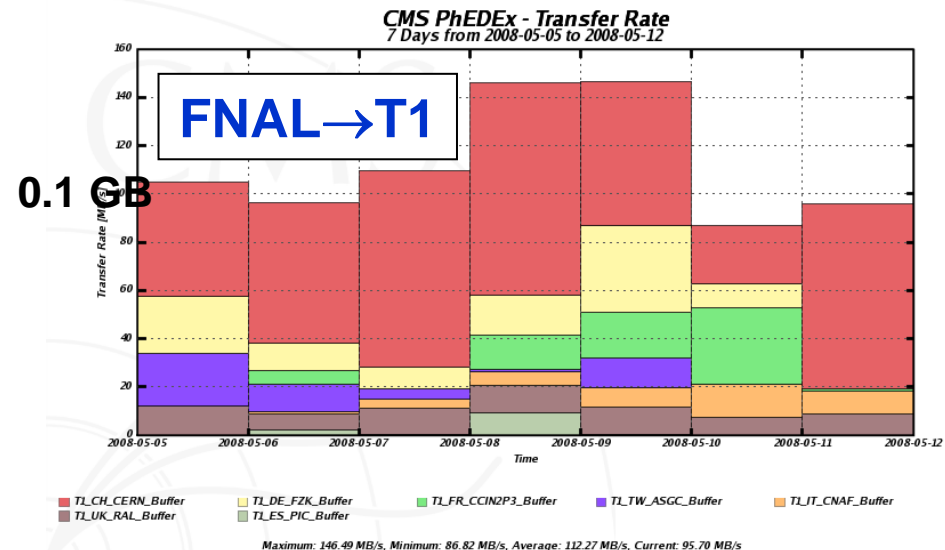
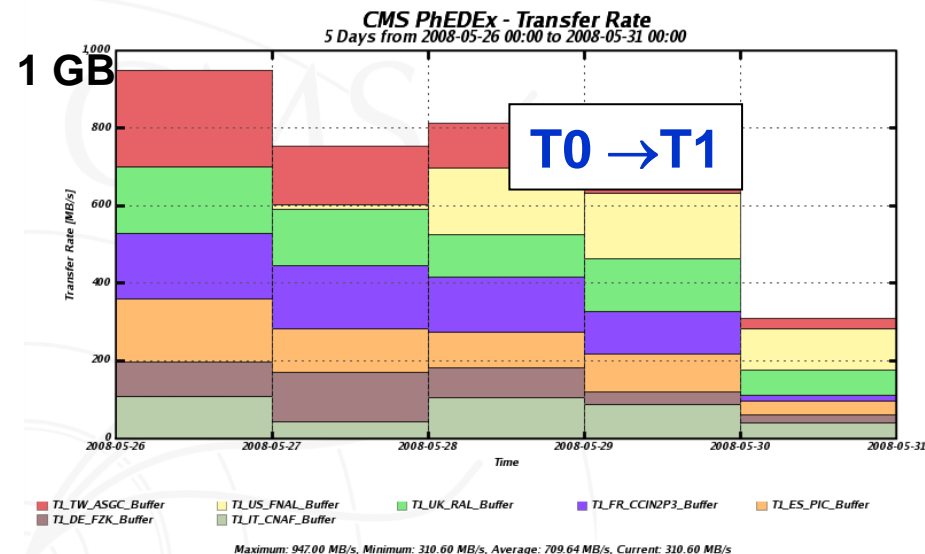
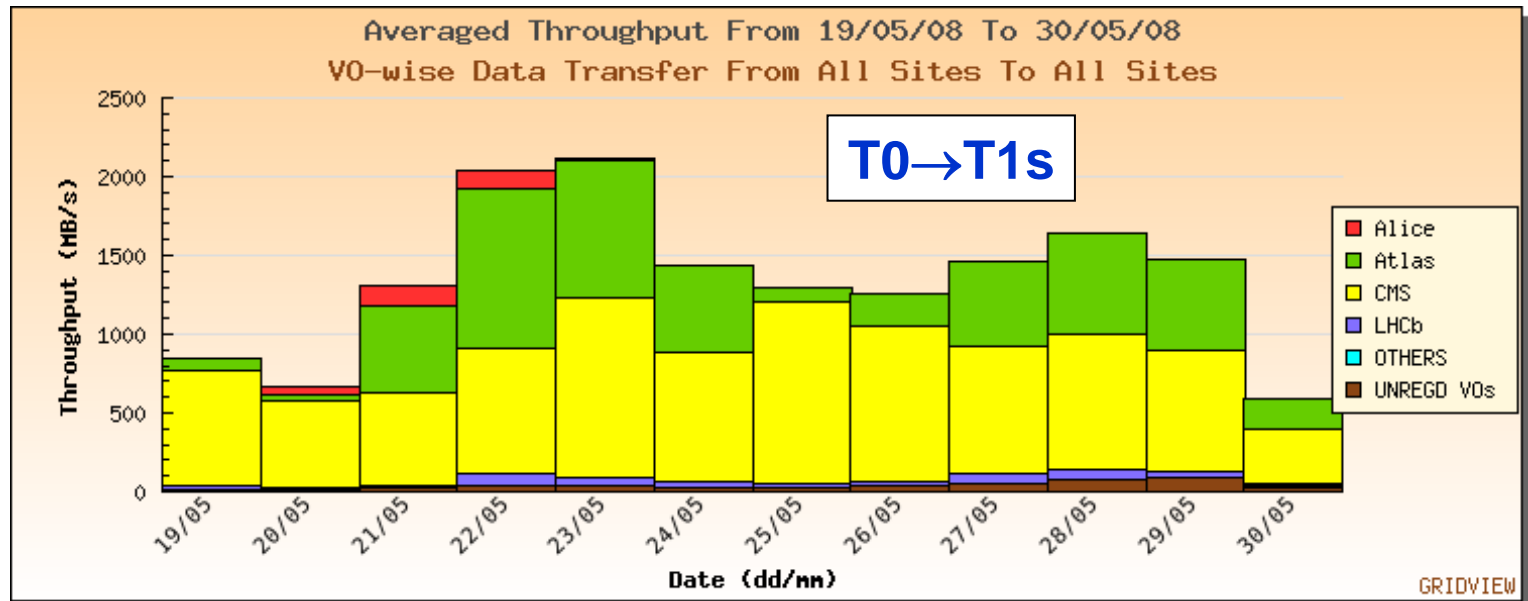
## Seven US Tier 2 centers:

- **Production computing and simulation**
- **Data analysis efforts**
- **Provided by NSF/university funds at Caltech, Florida, MIT, Nebraska, Purdue, UCSD, Wisconsin**

US CMS Tier-2 Summer 2008	CPU T2	1MSI2k	Tier-2 Processing Nodes
	Disk T2	200TB	dCache (200MB/s IO)
	Network	2.5-10Gb/s	WAN Networking
	People	2FTE	Supported Tier-2 Operations



# CCRC







## 6. Is CMS ready to analyze data and do physics?

- **A variety of physics analysis are being prepared that look at objects with relatively large cross sections**
  - ◆ Simple charged particle spectra
  - ◆ Single jets and dijets
  - ◆ W's and Z's
  - ◆ Dimuons
  - ◆ Top

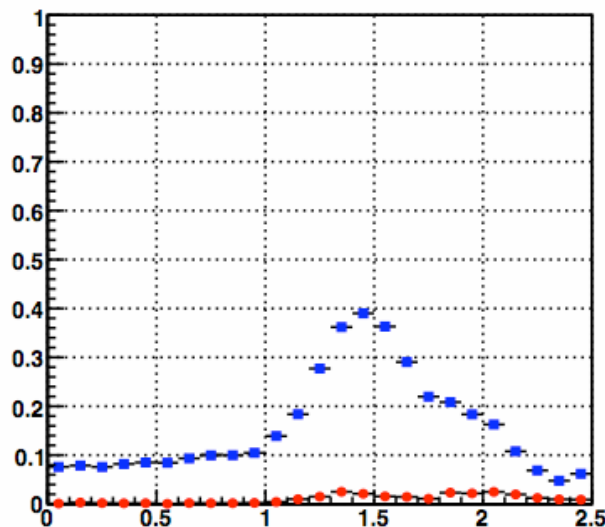
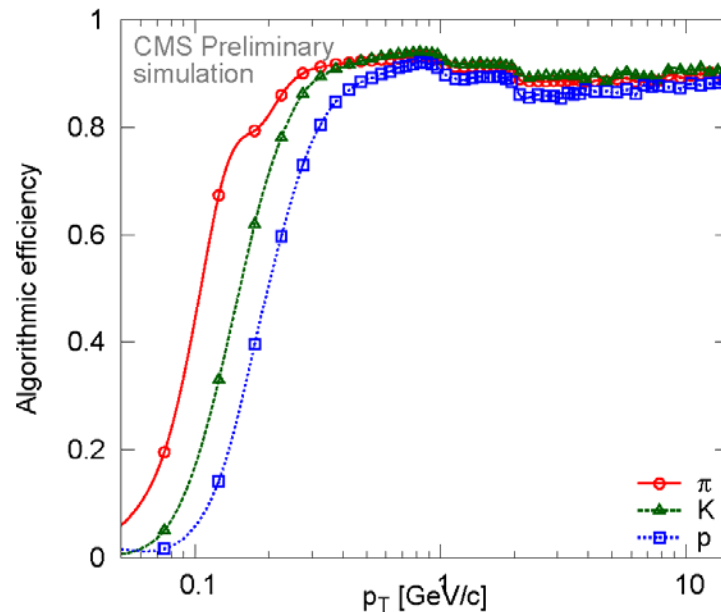
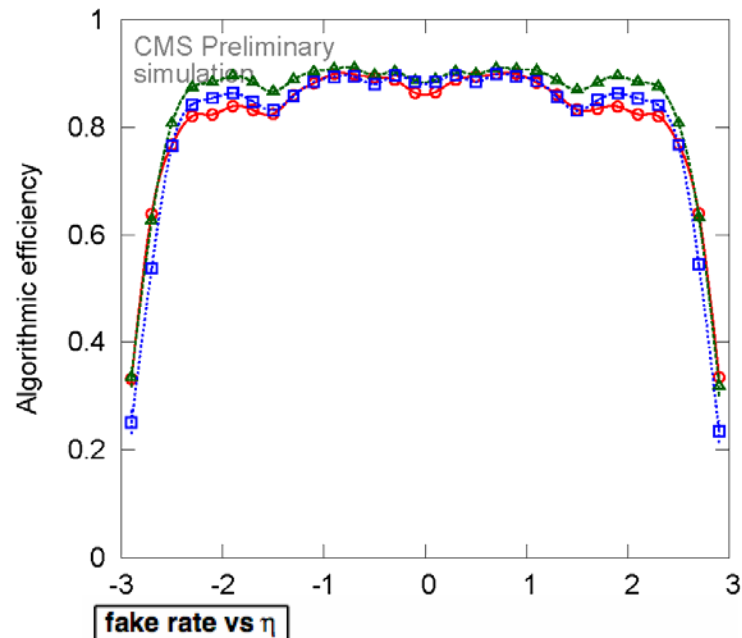


# Charged hadron spectra at LHC

- **An example of an analysis we have already rehearsed in real time!**
  - ◆ Teams working on CERN Analysis Facility (CAF) and Tier-2 facilities consisting of experts in tracking detector operation, alignment, calibration, and analysis!
  - ◆ Plan to be ready to go when data arrives
  
- **One of the first physics results from the LHC**
  - Will constrain QCD models of hadron production
  - Important tool for the calibration and understanding of the CMS detector



# Efficiency and purity to very low $p_T$



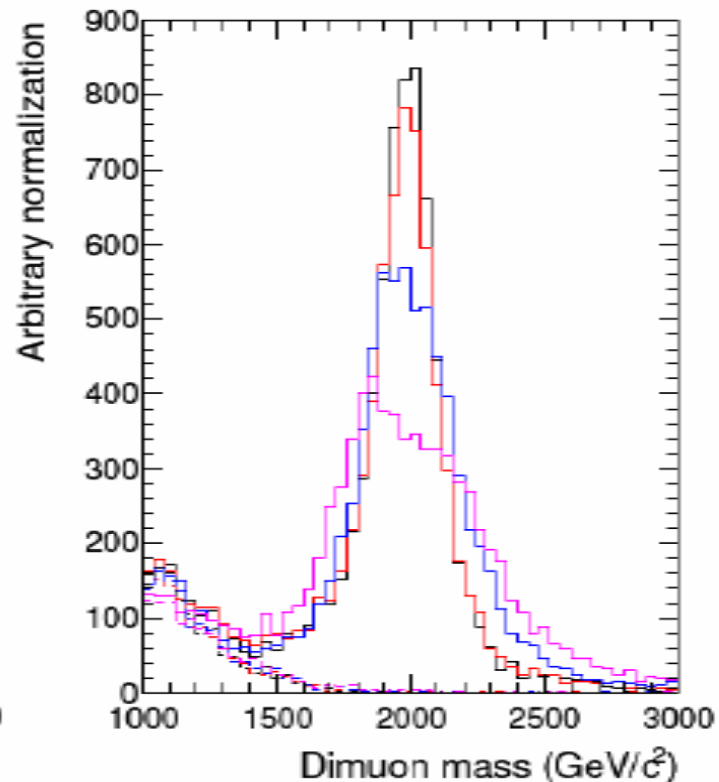
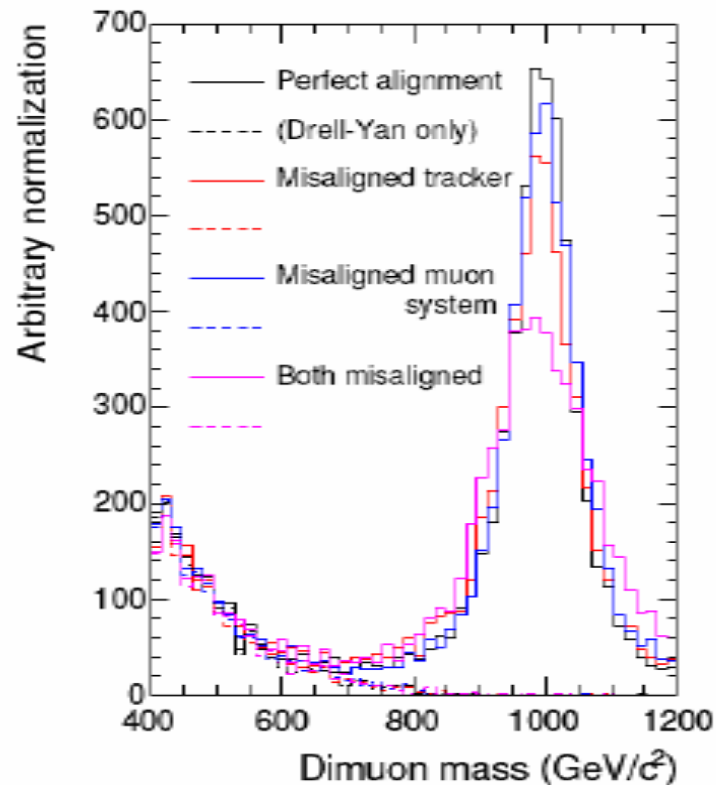
Blue is the previous fake rate. Red shows impact of recent improvements (iterative tracking methods and trajectory fitting/cleaning)



# Even higher momentum

- **Search for  $Z' \rightarrow \mu\mu$**

- ◆ **2 TeV  $Z'$  visibility not lost by initial alignments (already in hand).**



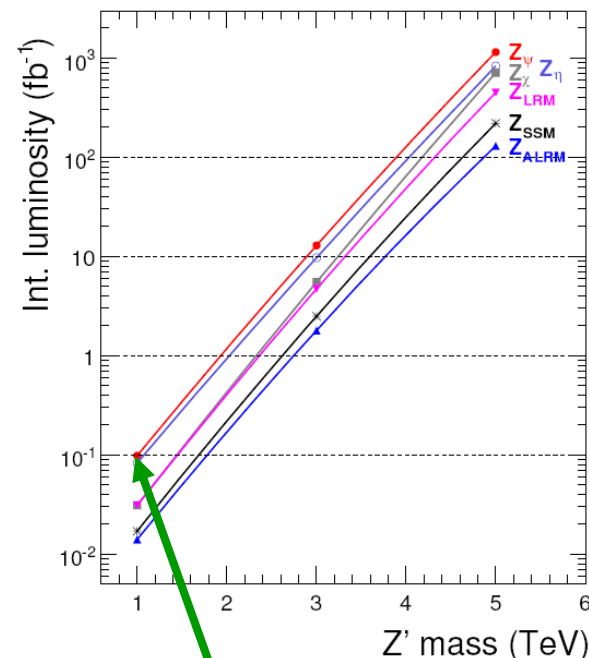
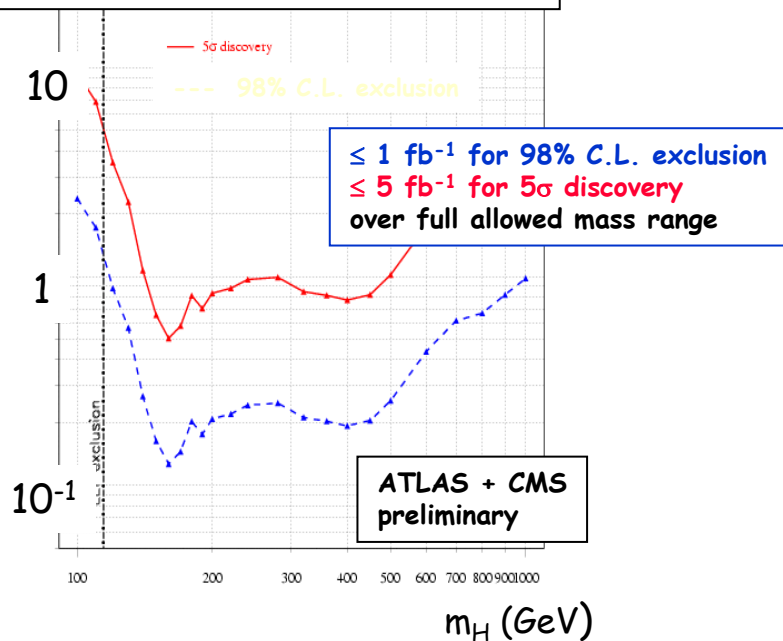




# 7. What might early physics looks like?

Channels (examples ...)	Events to tape for 100 pb <sup>-1</sup> ( per expt: ATLAS, CMS)	Total statistics from previous Colliders
$W \rightarrow \mu \nu$	$\sim 10^6$	$\sim 10^4$ LEP, $\sim 10^6$ Tevatron
$Z \rightarrow \mu \mu$	$\sim 10^5$	$\sim 10^6$ LEP, $\sim 10^5$ Tevatron
$t\bar{t} \rightarrow W b W b \rightarrow \mu \nu + X$	$\sim 10^4$	$\sim 10^4$ Tevatron
QCD jets $p_T > 1$ TeV	$> 10^3$	---
$\tilde{g}\tilde{g} \quad m = 1$ TeV	$\sim 50$	---

## Needed $\int L dt$ (fb<sup>-1</sup>) per exp



**TeV Low lumi 0.1 fb<sup>-1</sup> : discovery of 1-1.6 TeV possible**  
**High lumi 100 fb<sup>-1</sup>: extend range to 3.5-4.5**

The early physics can be exciting!



# Ready Enough

- **The LHC is a discovery machine**
  - ◆ There could be something new and exciting that shows up early
- **We have to be ready for this happy possibility by**
  - ◆ Having an analysis that is appropriate to the task presented by the available early luminosity
    - It does not have to be the asymptotically “best” analysis but just good enough
      - Especially in alignment and calibration
    - The analysis will continue to improve for many years as it continues to meet the challenge of the increasing event samples



# Summary

- Is the CMS Detector ready to take data? **YES**
- Is CMS ready to process data? **YES**
- Is CMS ready to analyze data and do physics? **YES**
- What might early physics looks like? **Exciting (maybe)!**
- Is there is still room for good people to join? **YES**

**LHC is the first machine capable of exploring the whole range of phenomena up to  $\sim 1$  TeV**

- We expect to find out what is responsible for electroweak symmetry breaking (Higgs or other?)
- We are likely to find something **NEW** to take care of the many problems with the Standard Model

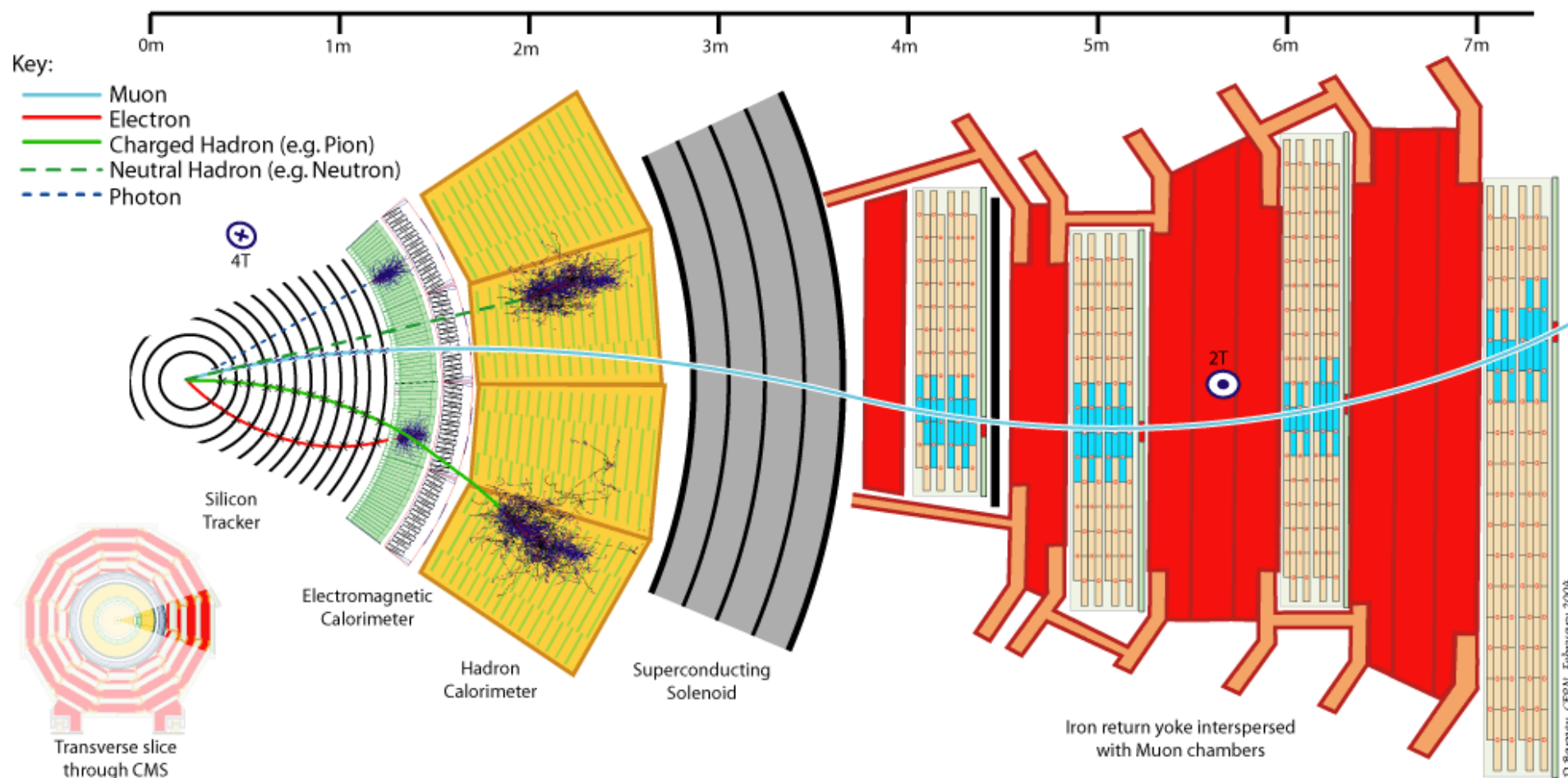


# Backup





# CMS Slice







# Fully cabled and dressed





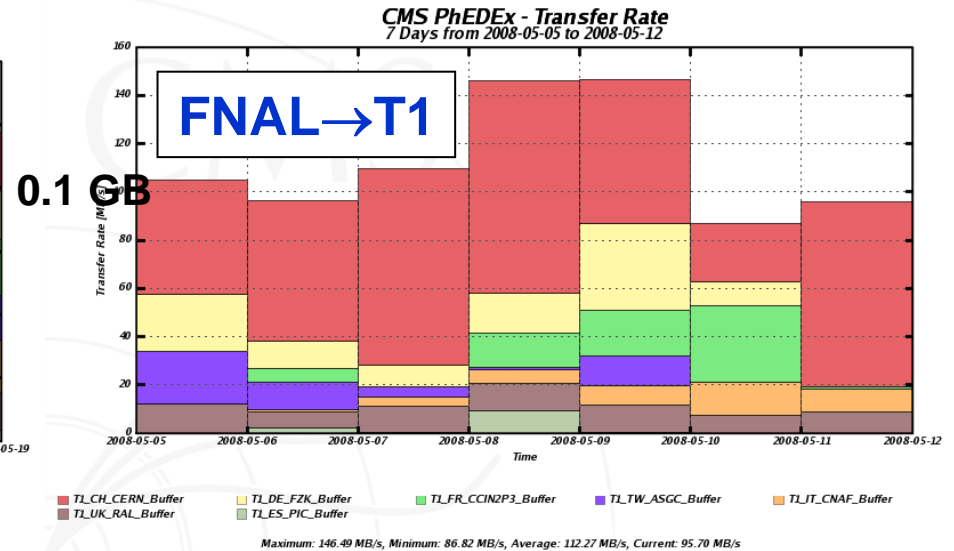
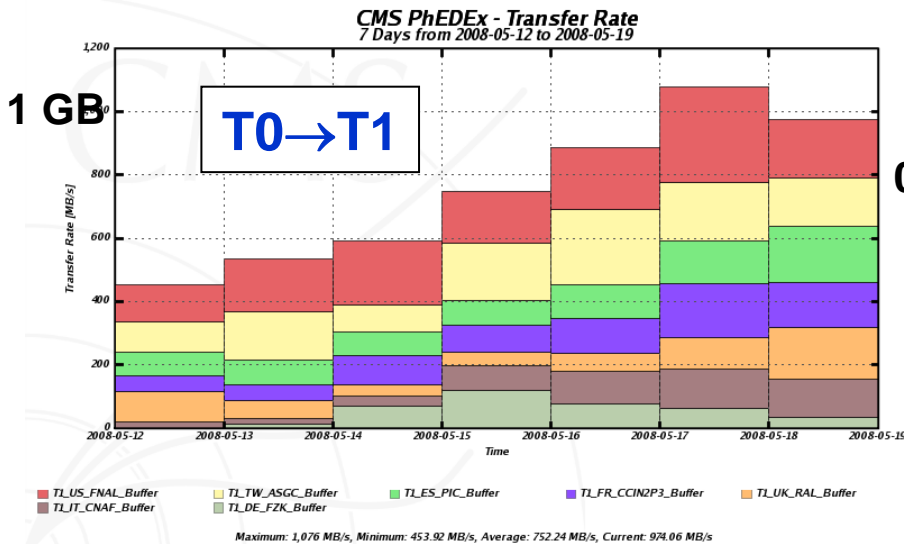
# LHC Facts – I

- **Tunnel (originally built for “Large Electron-Positron” Collider –LEP)**
  - ◆ Circumference: 26.659km
  - ◆ Tilt: 1.4° (122m)
- **Number of magnets**
  - ◆ Main dipoles: 1232
    - Magnetic field: 8.33 Tesla (@7 TeV)
    - Two beam tubes and coils with opposite fields to guide two counter-circulating proton the beams
  - ◆ Main quadrupoles: 858
  - ◆ Correction magnets: 6208
  - ◆ Total magnets: ~9300
- **Operating temperature: 1.9°K**
  - ◆ Helium is superfluid
- **RF cavities: 8/beam at 5.5MV/m @ 400.8 MHz**
- **Revolution frequency: 11.2455 KHz**
- **Power consumption: ~120MW**





# CCRC/CSA08



**Up to now schedule has been kept for essential components of CSA08**

**Week 1 (5-11 May)** S43 prompt reconstruction at T0

**Week 2 (12-18 May):** S43 prompt calibration/alignment exercises on CAF  
S156 prompt reconstruction at T0

**Week 3 (19-25 May):** S156 prompt calibration/alignment exercises on CAF  
S43 re-reco at T1s using constants from S43 exercises

**Week 4 (26May- 1Jun):** S156 re-reco at T1s using constants from S156 exercises

**All CSA08 production to stop 2nd June**

**From 2nd June:** Physics analyses using re-reco S156 data at CAF/T2s



# CCRC: All Four LHC Experiments

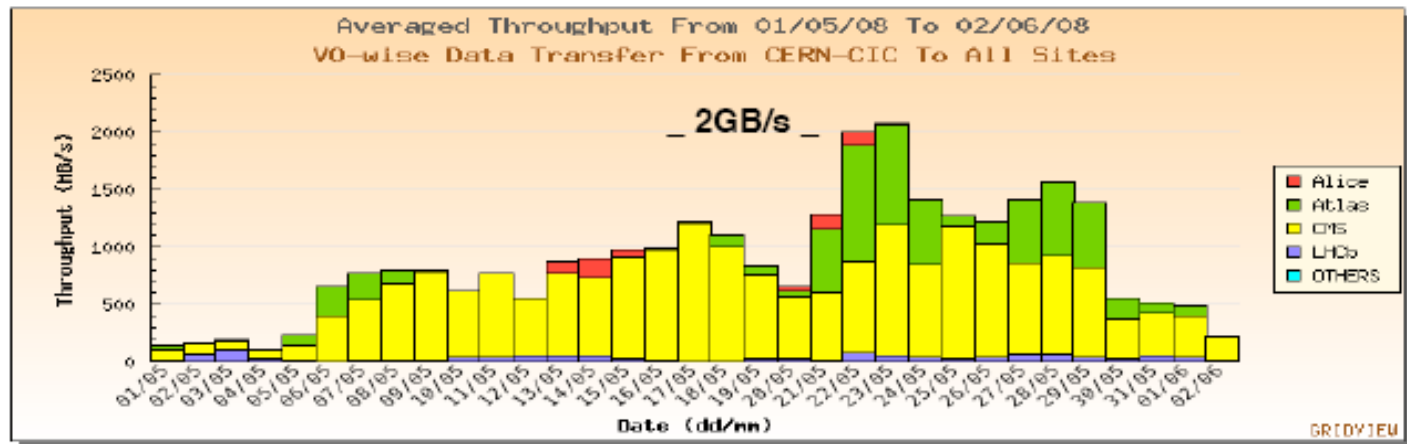
Regular, daily operational meetings organized by WLCG (J.Shiers)

- Attended by experiments, T0, T1 and T2 sites
- Experiments status and plans presented (for CMS: D.Bonacorsi)
- Mostly operational issues discussed

Very effective to solve operational issues

Little “cross-experiment” coordination and scheduling

- Each experiment had full schedule of activities
- Some correlated tests planned at sites (collect information now)





# News from Meeting with Directorate, Machine and Experiments & LHCC

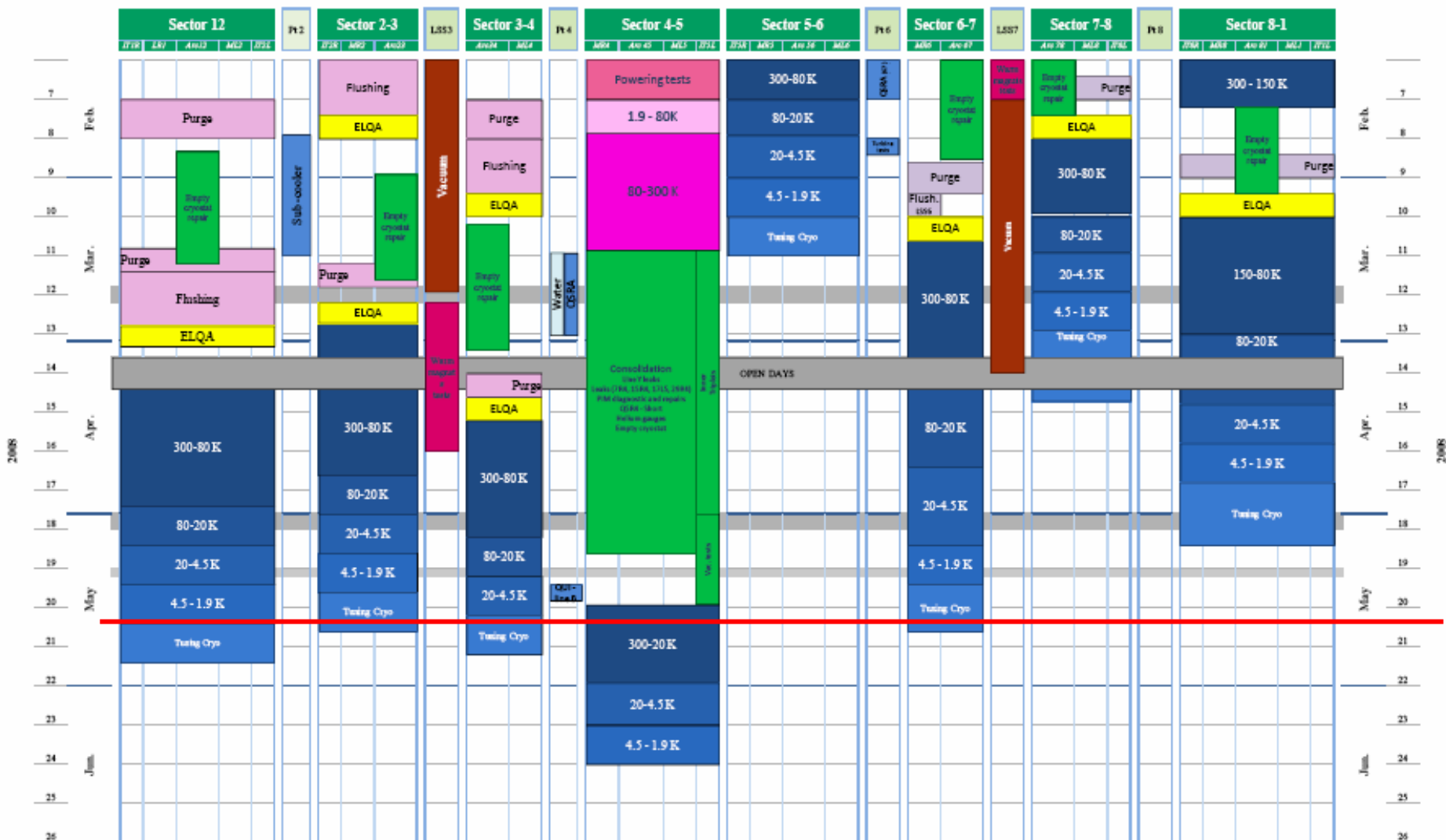
1. **Experiments should aim to be closed by mid-July.** From the viewpoint of CMS mid-July is arrived at by adding 5 weeks to the moment when our beam-pipe has been baked out (targeted for 7th June). The five weeks are used for the installation of the pixels and one-endcap and the closure of CMS.
2. After closure access will be controlled. **Injection of beam foreseen 10 days to two weeks later. Collisions at 10 TeV are expected two months later.**
3. **There will be a winter shutdown.**
4. The **next meeting** to discuss the schedules will take place at the **end of June** when the machine should be cold and the beam-pipes of experiments should be closed and baked out.
5. We must be prepared to take advantage of any opportunities that may arise due to any changes in the schedules and be ready to install the remaining elements of the ECAL endcaps and preshower.
6. LHCC Mini-Review. The Reviewers visited Point 5 and Bat 867 (the ECAL electronics integration centre). Very impressed by the clearly visible and substantial progress made since their last meeting. "Breaking news" during the session comprised results from the first day of CRUZET (Cosmics RUN atZEro Tesla) and the successful pixels/BCM trial insertion and extraction during the Monday and Tuesday.





# Cooldown Schedule

General Coordination Schedule - wk.10





# All Hadronic Spectra

